# Modeling the Effects of Aerosols on Precipitation in the Western U.S.

L. Ruby Leung and Steven J. Ghan
Pacific Northwest National Laboratory

Danny Rosenfeld, Alexander Khain, Barry Lynn, Amir Givati
Hebrew University of Jerusalem

Fourth Annual California Climate Change Conference
September 10 – 13, 2007
Sacramento, CA

# Background

- Over 80% of water supply in the western U.S. is provided by snowmelt runoff; long term changes in temperature and precipitation can have significant impacts on snowpack

- Aerosols serve as sites for cloud-drop nucleation. Higher concentrations of aerosol particles can lead to smaller cloud droplets, as more cloud condensation nuclei (CCN) are activated and compete for the water

- Smaller cloud droplets are less efficient in the cloud microphysical coalescence or collection process that produces raindrops, and the formation of ice particles and cold-precipitation processes are prohibited when cloud droplets are less than 12 $\mu$m in size

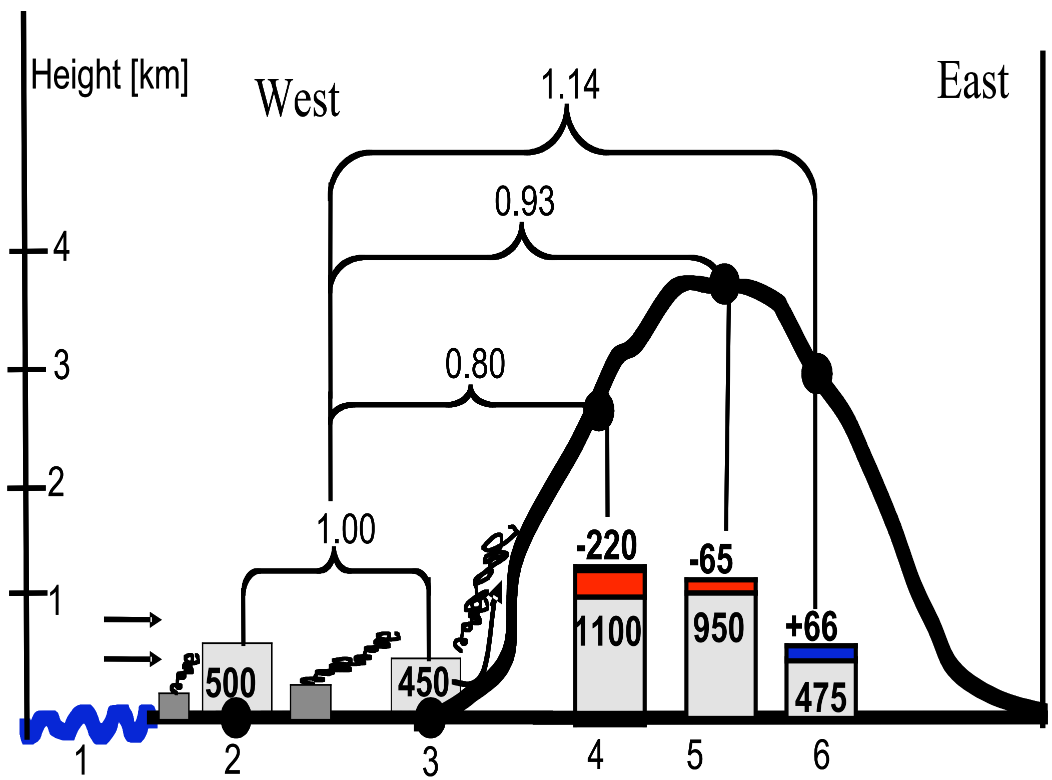
- Increase in aerosols due to air pollution may suppress precipitation, which can influence snowpack and streamflow

# Hypothesis

- Aerosols can reduce the orographic enhancement of precipitation in mountains downwind of urban areas and result in <u>redistribution</u> of precipitation from the ridges to the semi-desert lowlands, and a <u>net loss</u> of precipitation and snowpack in the mountains

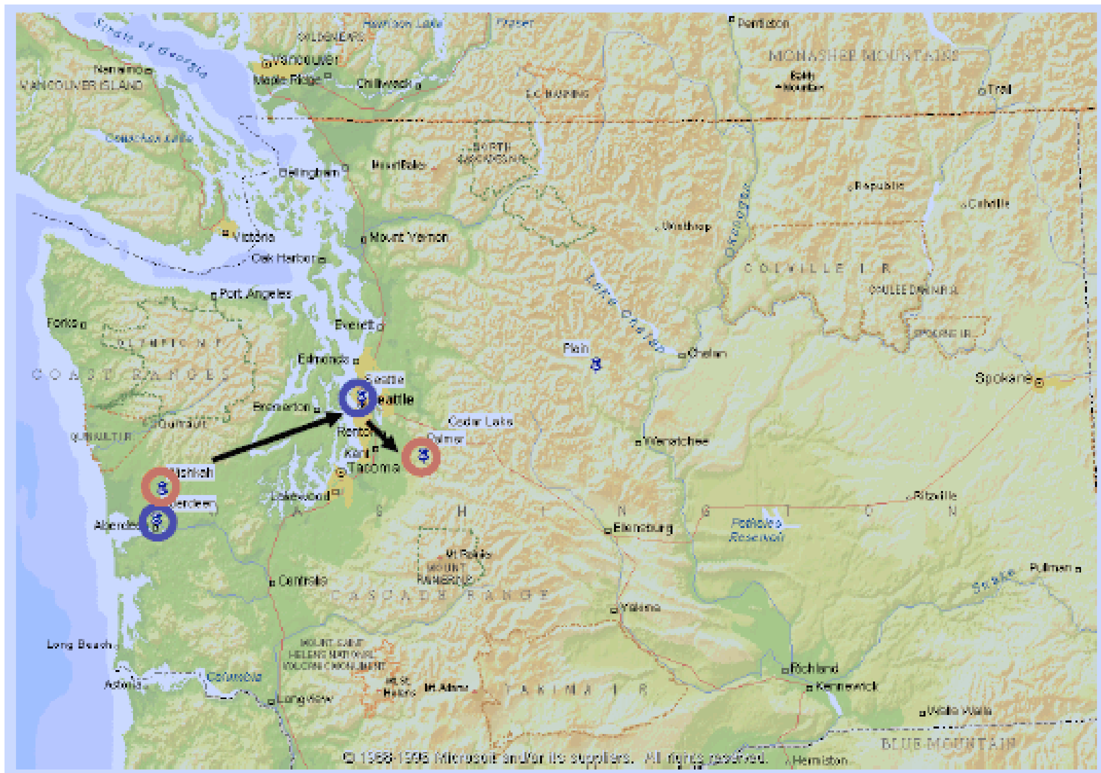
# Some Observational Evidence

**Topographic cross section showing effects of urban air pollution on precipitation as clouds move from west to east to the Sierra Nevada and eastern slopes**




**From Givati and Rosenfeld (2004)**

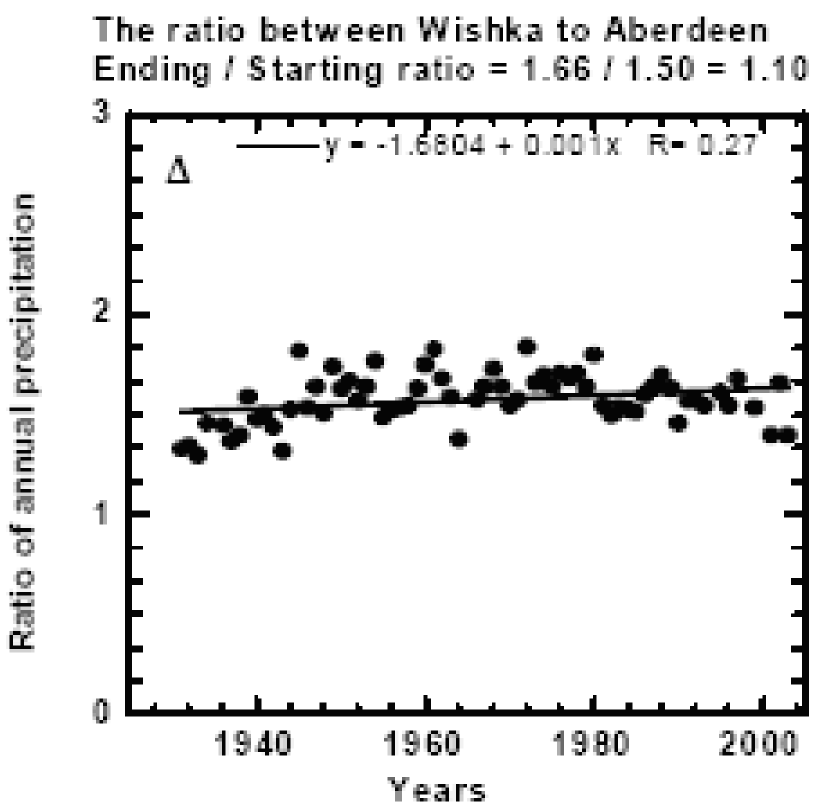
# More Recent Analysis in WA



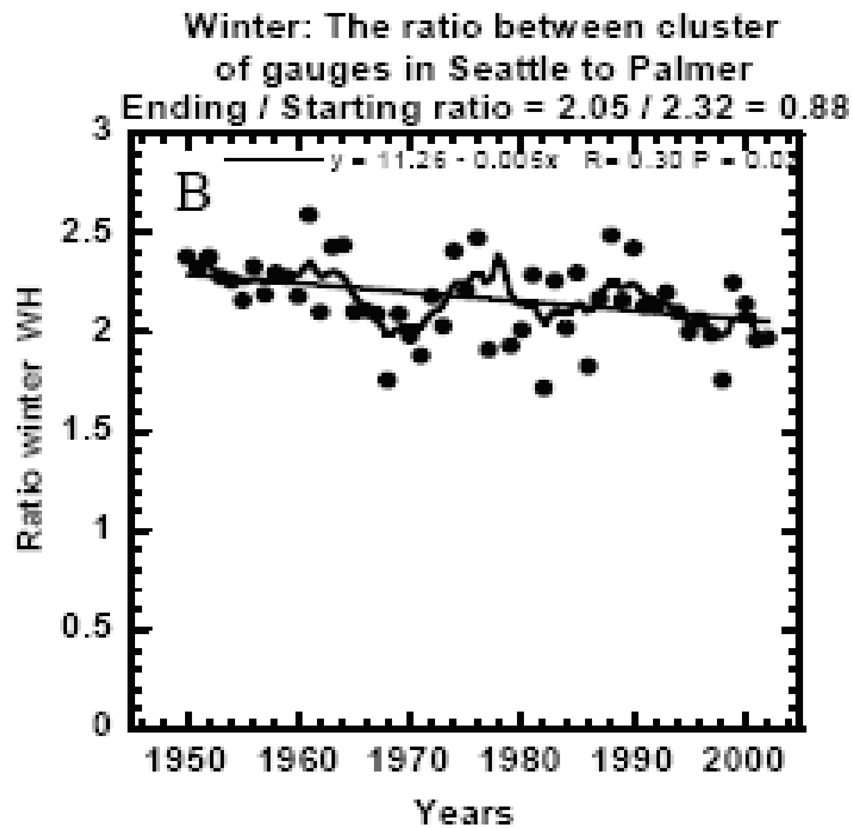

**Two pairs of plain/hilly stations in relatively pristine (Olympic Peninsula) and polluted (Seattle) areas**

# Trends in the Orographic Enhancement Factor

**Olympic Peninsula: Increasing trend**

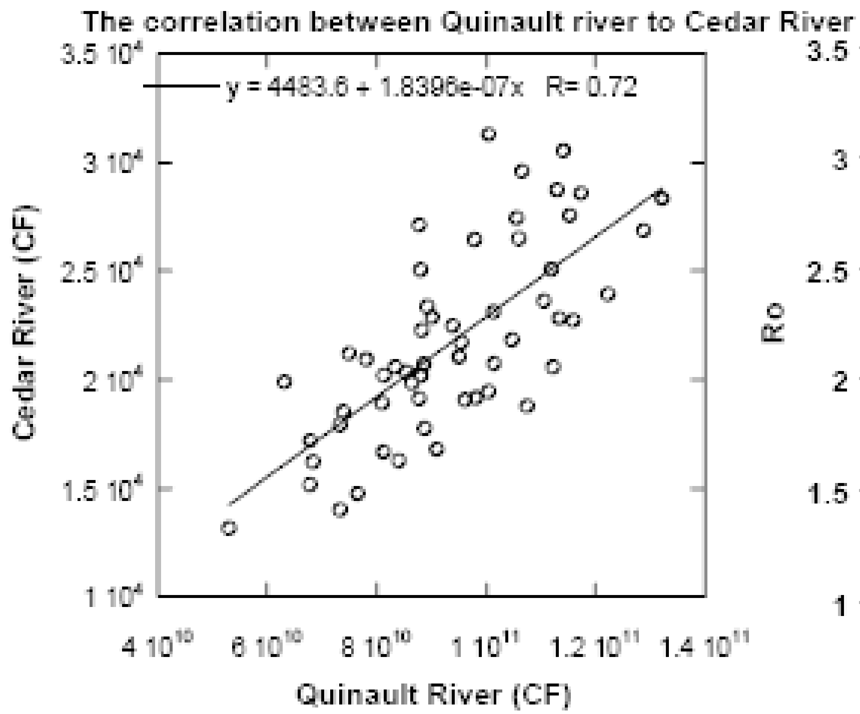


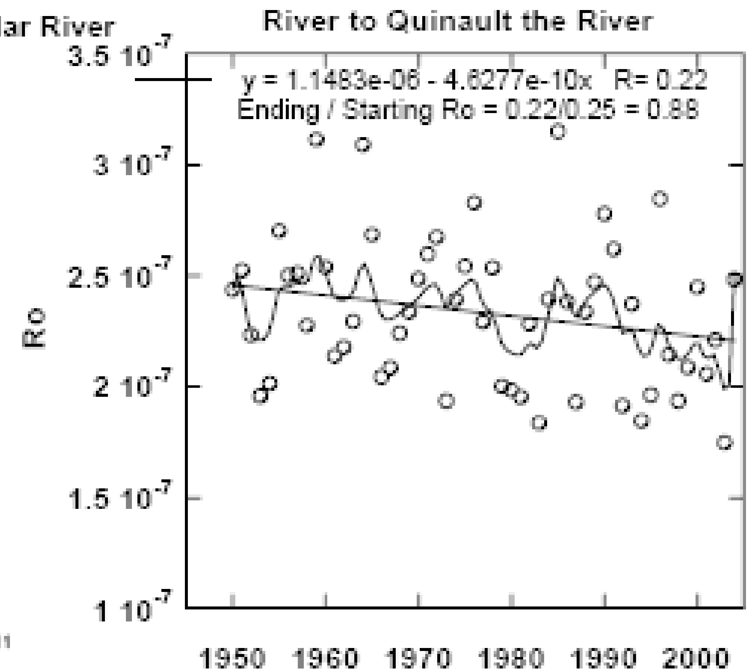

**Seattle Area: Decreasing trend**



# Consistency with Streamflow Data

Runoff / Runoff relationships



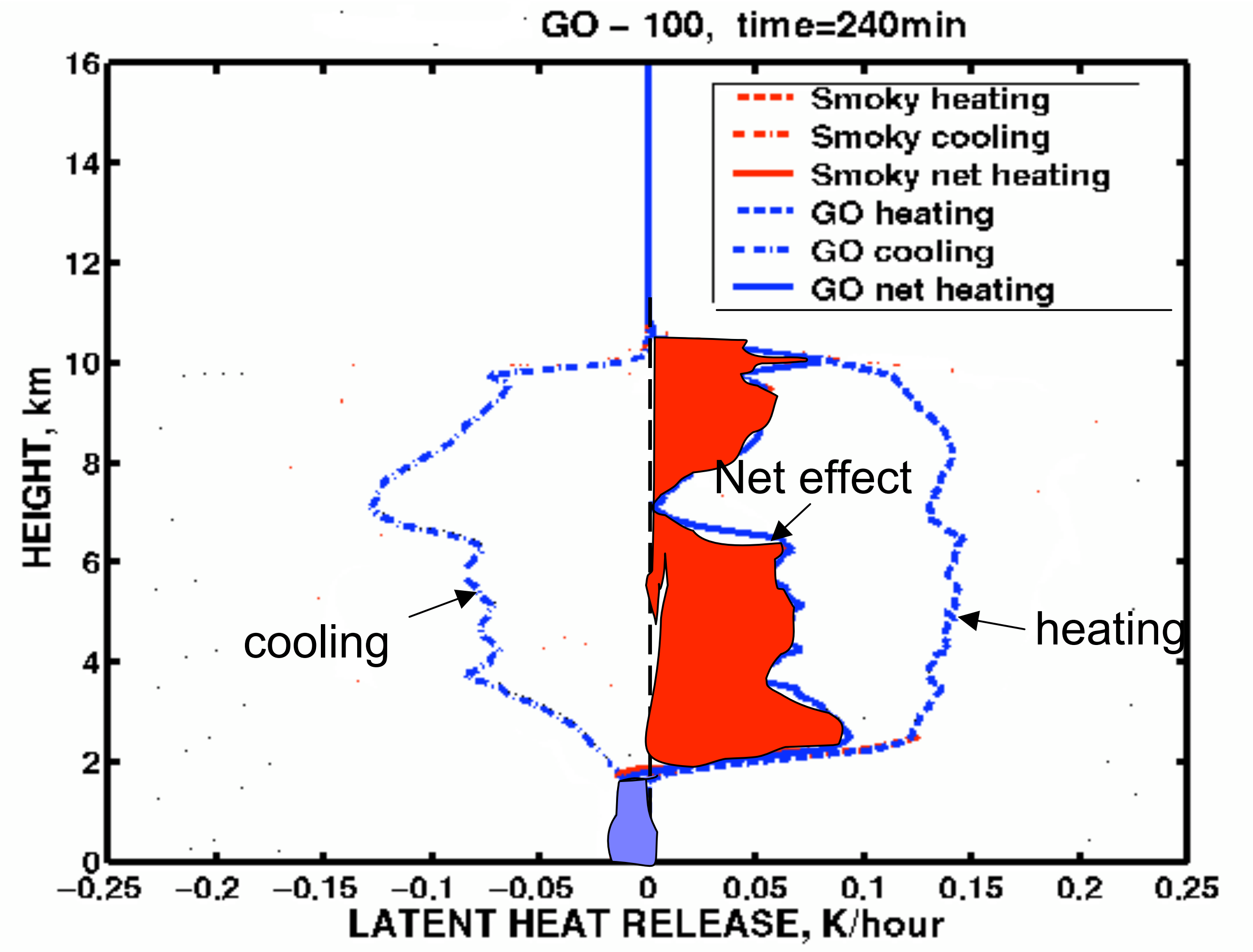




**Streamflow in the Quinault River (Olympic Peninsula) is highly correlated with streamflow in the Cedar River (Seattle area), suggesting that they are influenced by the same synoptic systems**

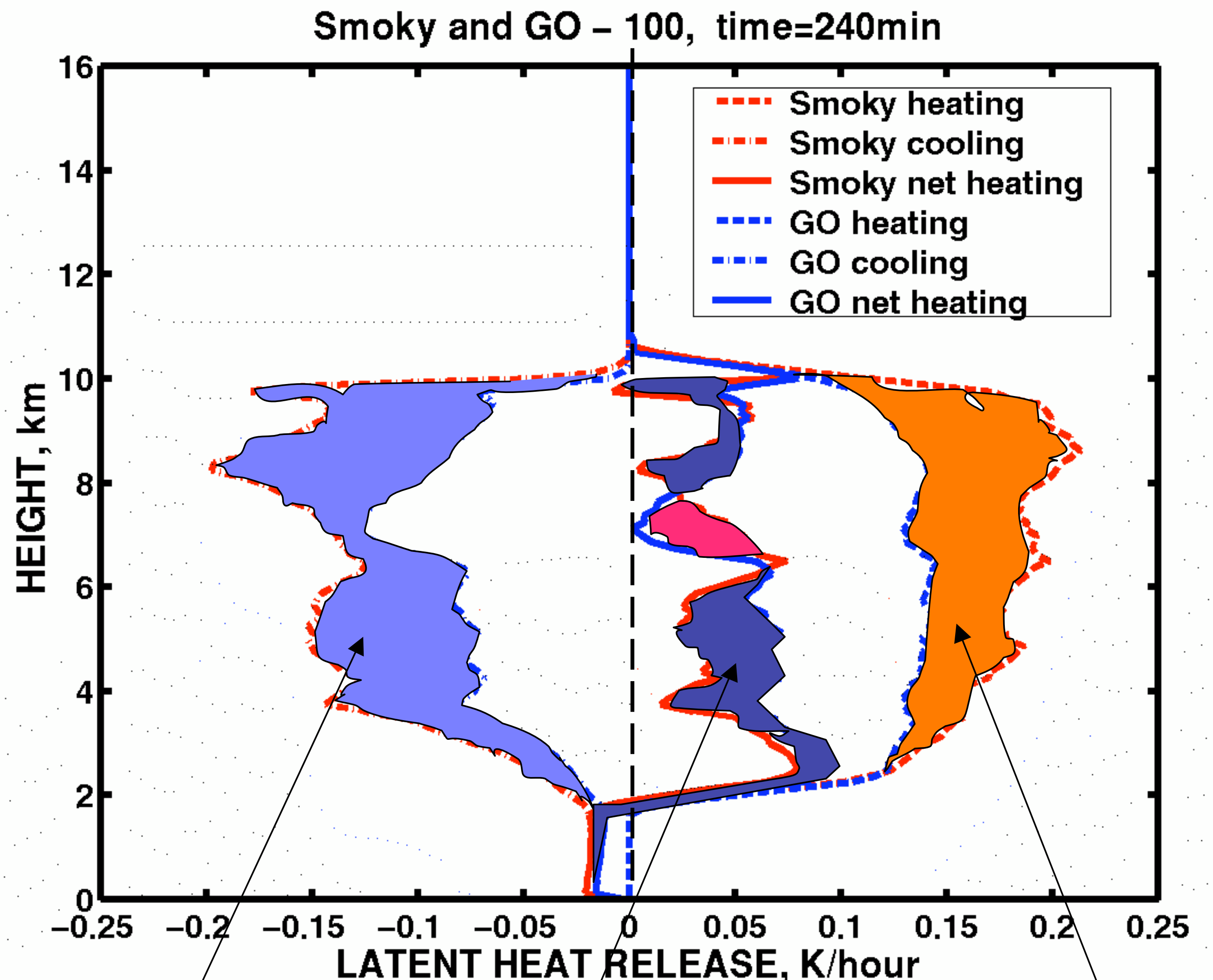
**Ratio between streamflow in the Cedar River and Quinault River shows a reduction over time**

# Can we use modeling to test our hypothesis and predict future changes?

# Precipitation is a small difference of two large quantities (gain vs loss)




**Source: Alexander Khain**




Cooling in polluted clouds is larger

Net effect: heating (=precipitation) is larger in clean air cloud

Heating in polluted clouds is larger

# A Major Challenge in Assessing Precipitation Change

**Precipitation** = GAIN (condensation+ ice deposition) - LOSS (evaporation+ ice sublimation)

Precipitation is often a small difference of large values

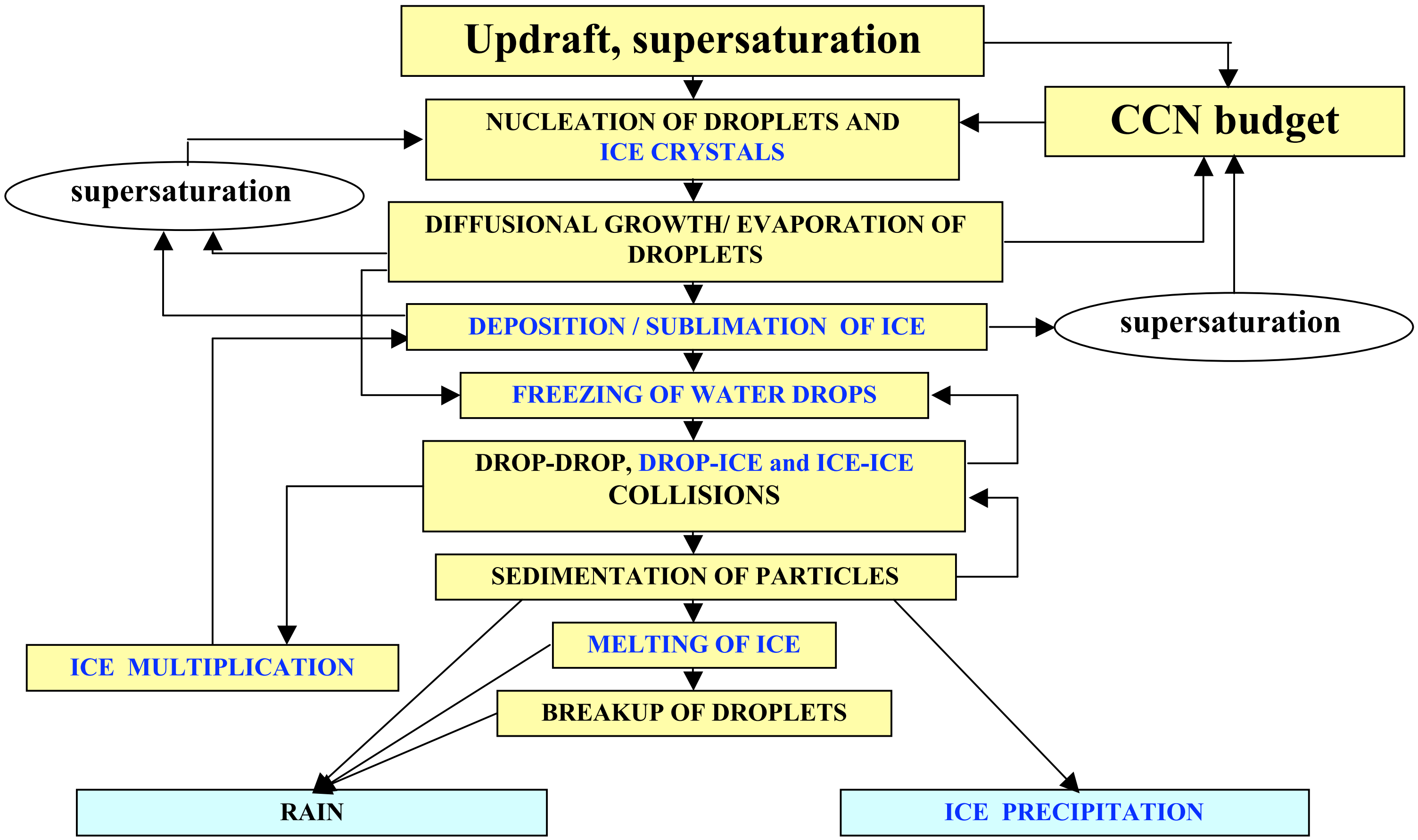
Aerosols affect both GAIN and LOSS

**ΔPrecipitation** = ΔGAIN - Δ LOSS

**Aerosols affect both generation and loss of hydrometeor mass**

**Source: Alexander Khain**

# MICROPHYSICAL SCHEME OF THE HEBREW UNIVERSITY CLOUD MODEL (HUCM)




**Each type of cloud particles is described by a mass distribution function represented by several tens of bins that changes in time**

**In contrast, BMP only predict mass, with assumed size distribution and prescribed droplet number density**

# A Prognostic Cloud Droplet Number Parameterization for BMP Scheme (Ghan, Leung, Easter 1997)

$$\frac{\partial N_k}{\partial t} = -(V \bullet \nabla N)_k + D_{k+1/2} \frac{\min(f_k, f_{k+1}) N_{k+1} / f_{k+1} - N_k}{(z_{k+1} - z_k)(z_{k+1/2} - z_{k-1/2})} + D_{k-1/2} \frac{\min(f_k, f_{k-1}) N_{k-1} / f_{k-1} - N_k}{(z_k - z_{k-1})(z_{k+1/2} - z_{k-1/2})} + S_k - A_k - C_k - E_k$$

**$N_k$ = droplet number mixing ratio in layer *k***

**$D_k$ = vertical diffusivity at interface between layers *k* and *k*+1**

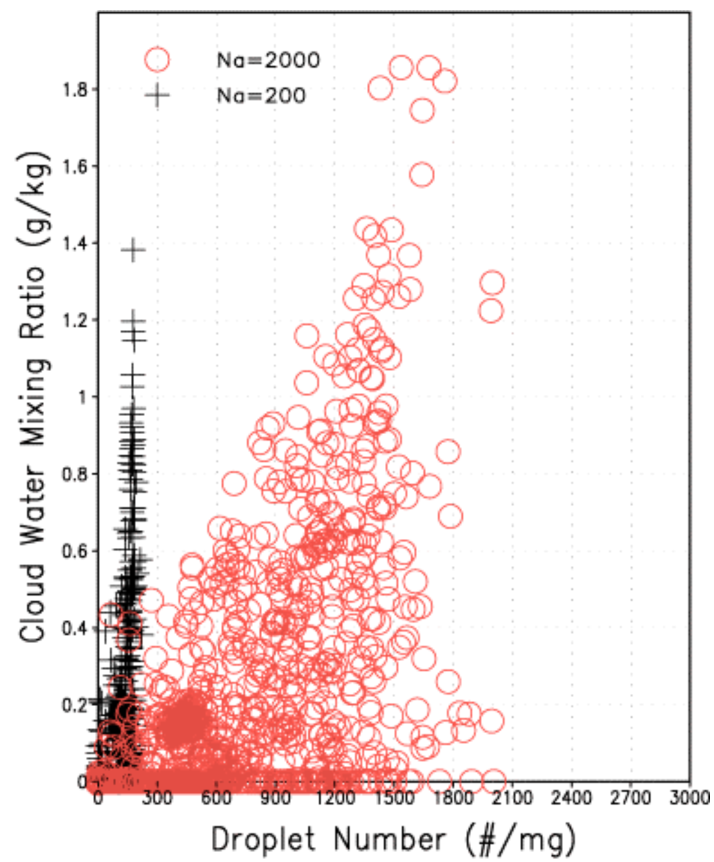
**$f_k$ = liquid cloud fraction in layer k**

**$S_k$ = droplet nucleation source in layer k**

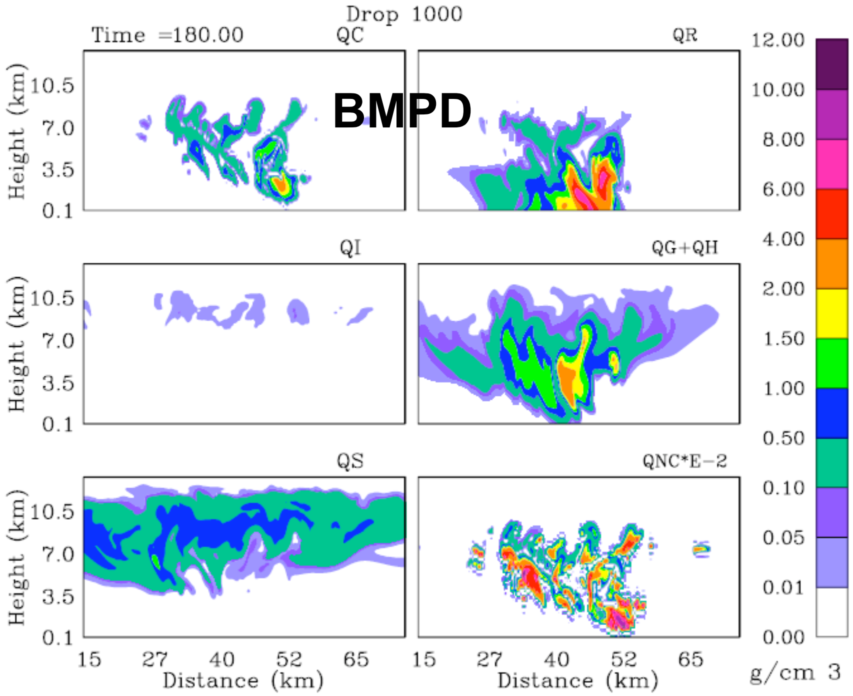
**$A_k$ = droplet loss by autoconversion of droplets**

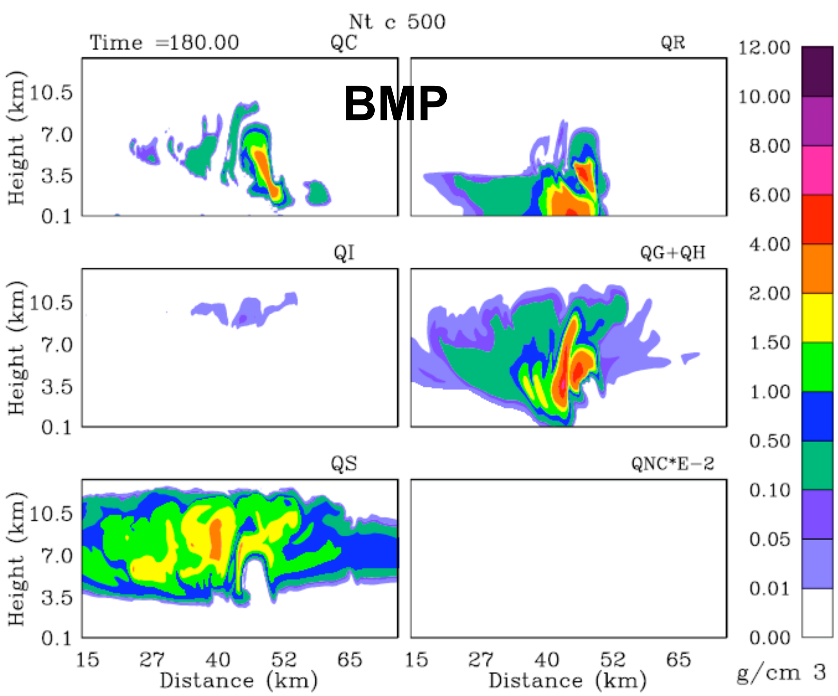
**$C_k$ = droplet loss by collection by precipitation**

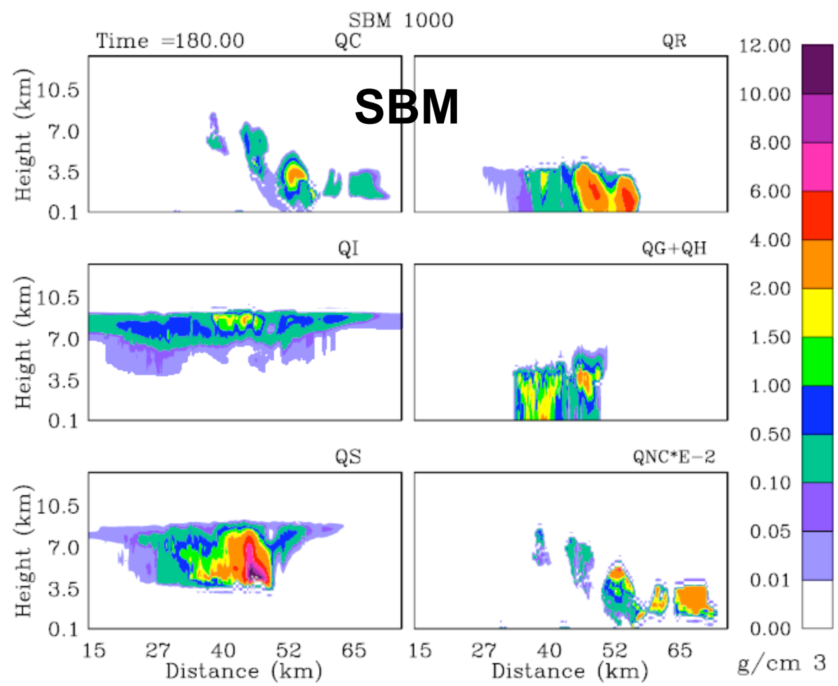
**$E_k$ = droplet loss by evaporation**



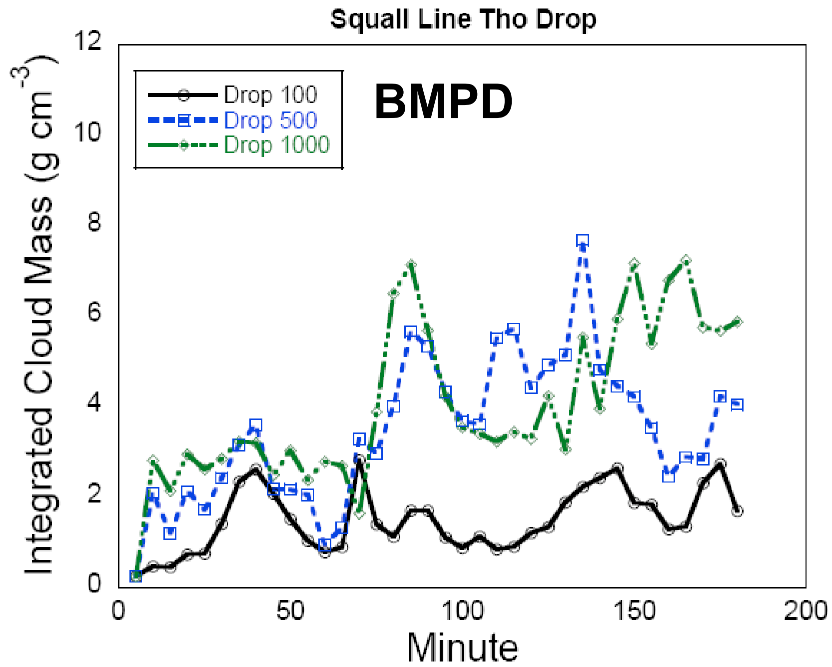
# A Comparison of Three Different Cloud Microphysical Representations Implemented in WRF

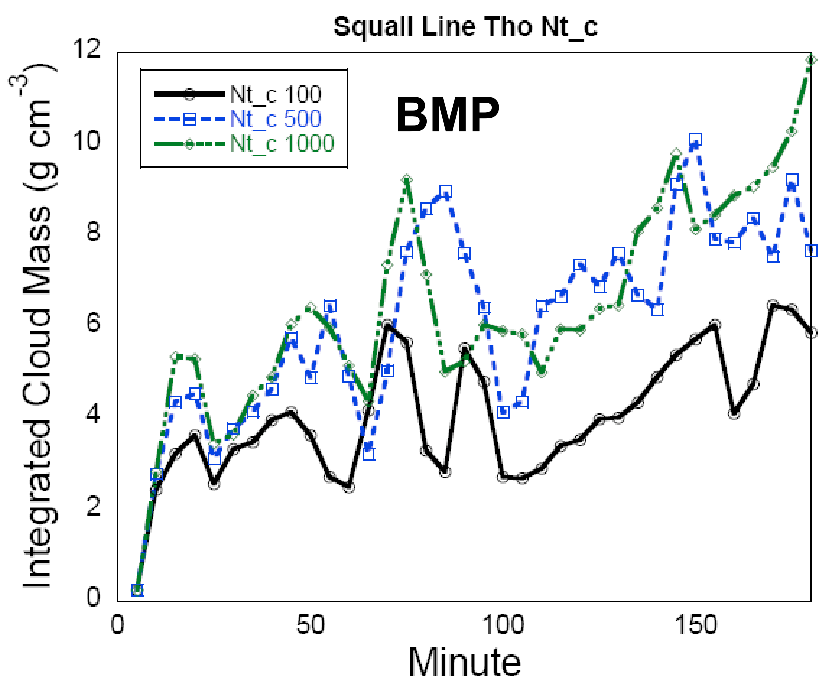


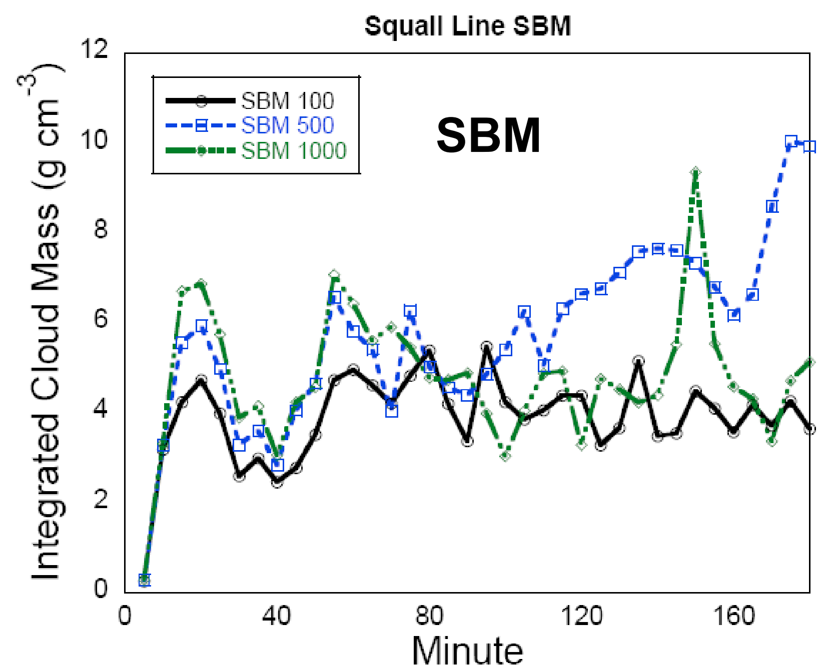



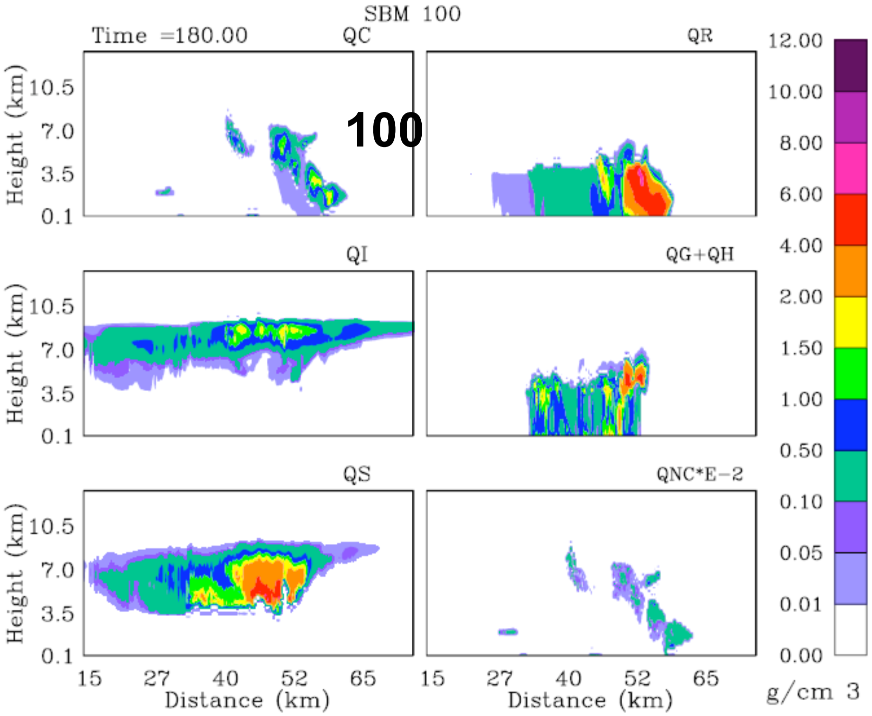
# A Comparison of Three Different Cloud Microphysical Representations Implemented in WRF

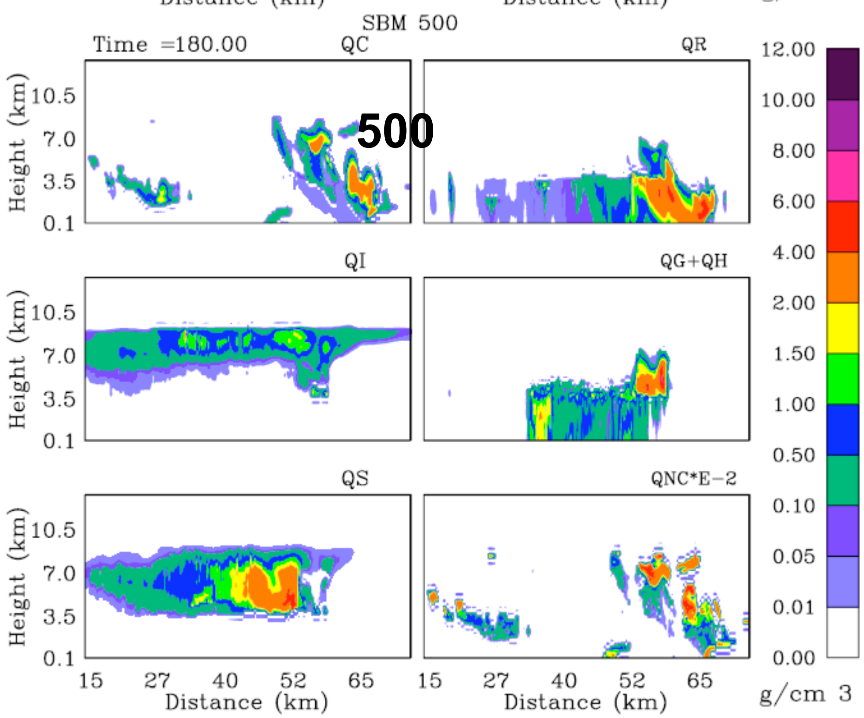


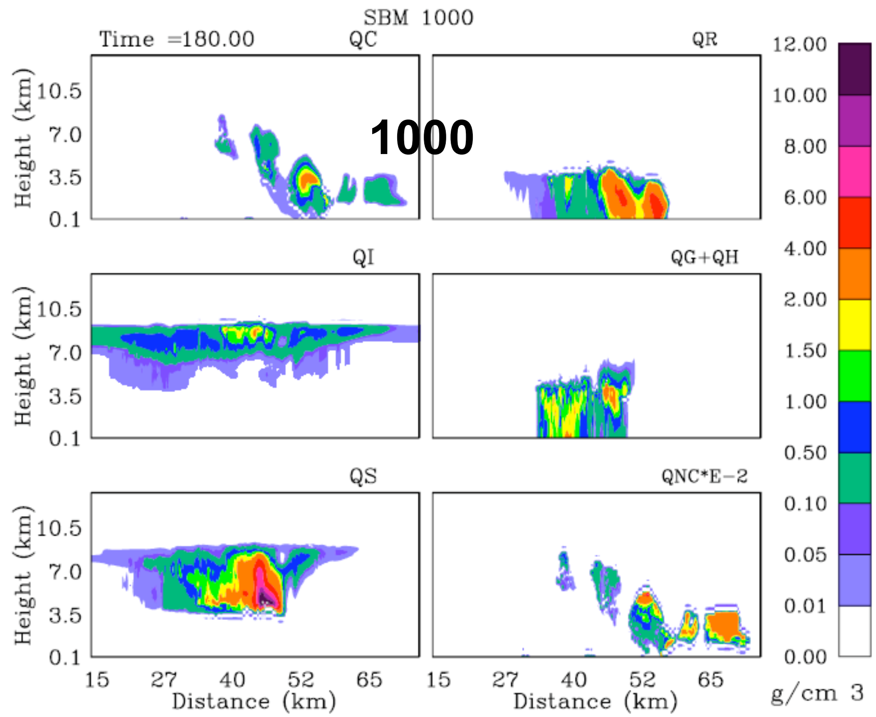



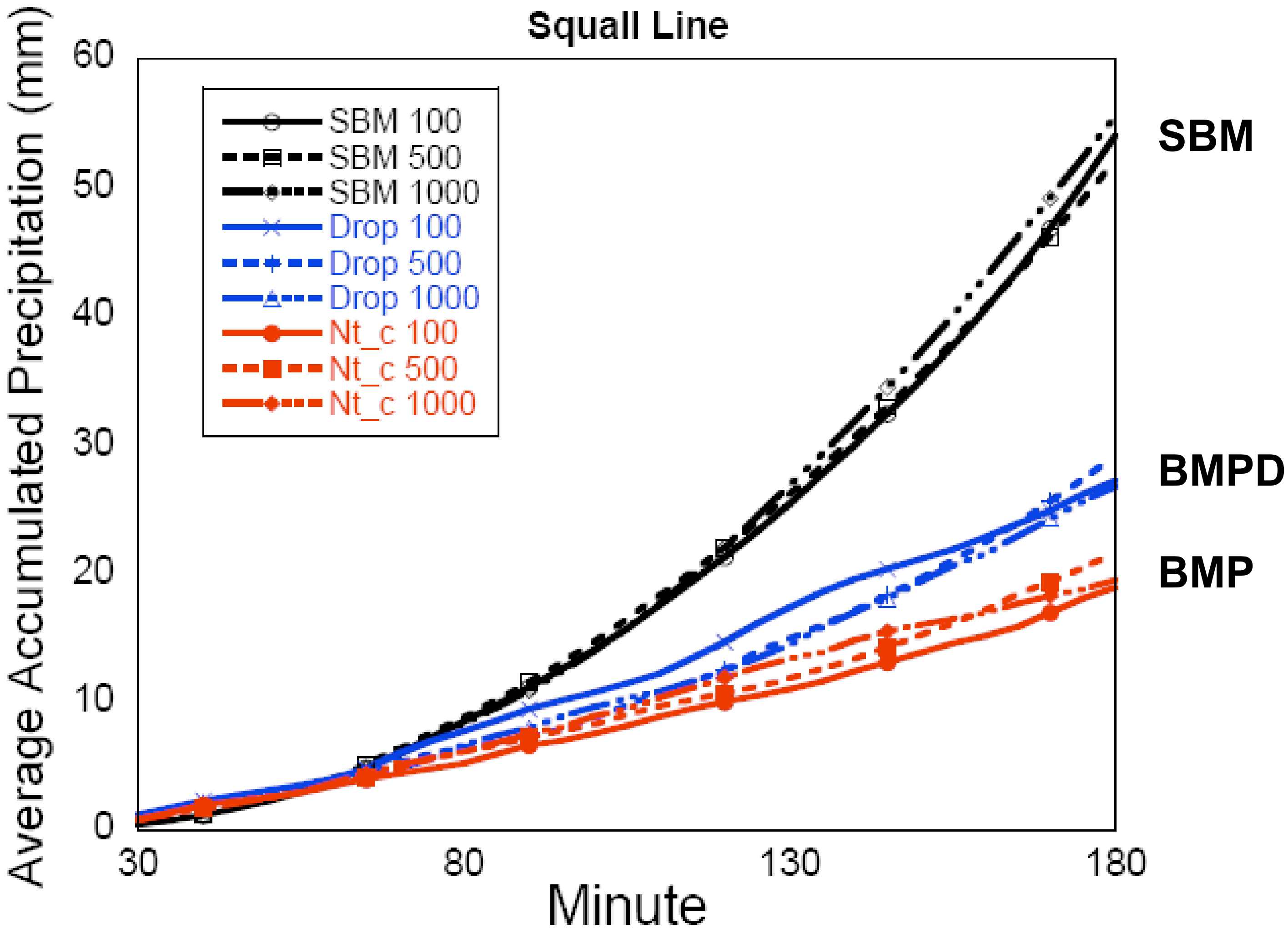
# Aerosols affect the cloud microphysical structures



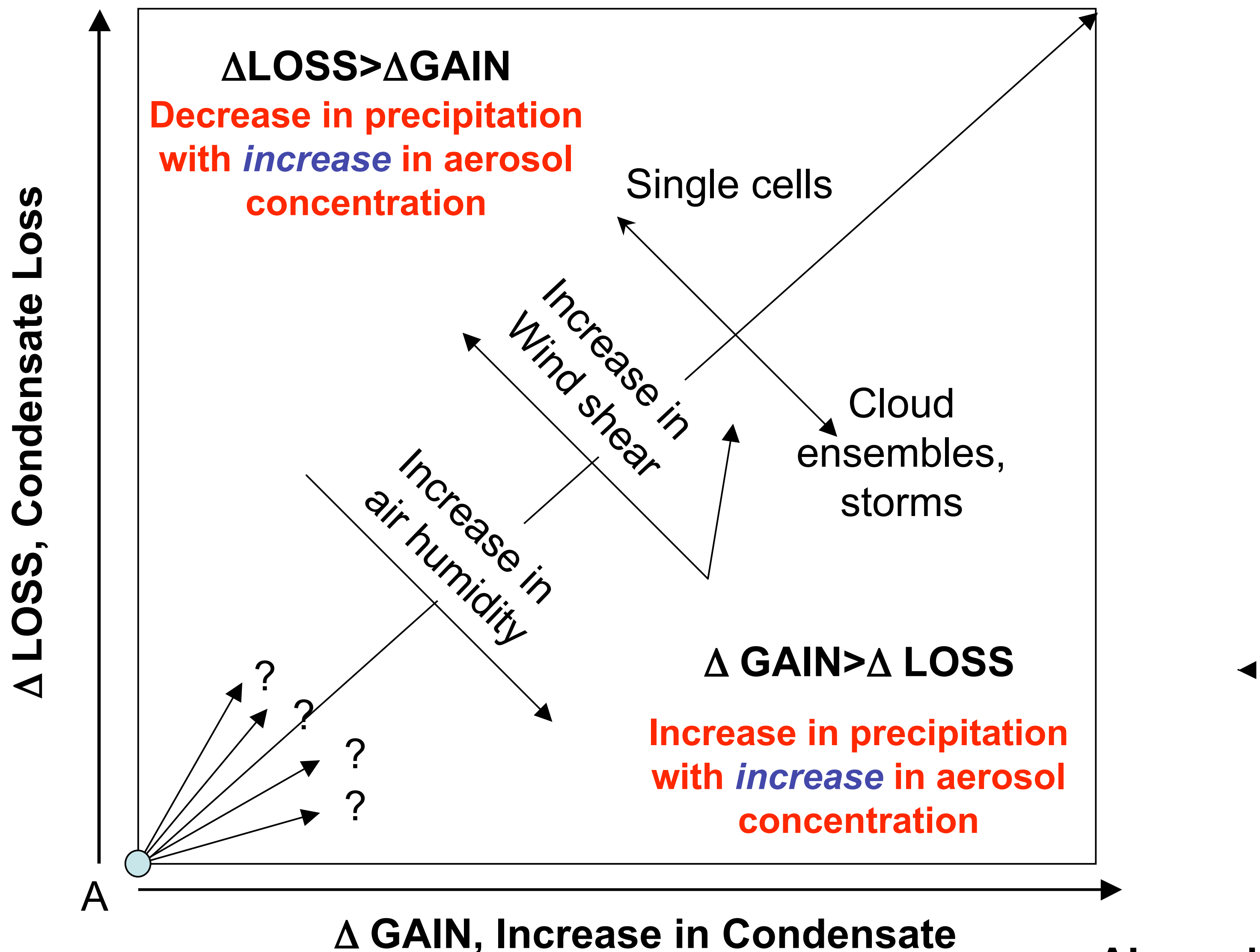



# Differences among schemes are larger than sensitivities to aerosol concentrations



# Possible scenarios of aerosol effects on precipitation for squall line




**Alexander Khain**

# Challenges in modeling aerosol effects on orographic precipitation

- The complex orography of the western U.S. presents a myriad of spatial scales
- Cloud microphysical processes are complex and observations are lacking
- Environmental conditions vary at the seasonal to interannual time scales

# Approach

- Apply the SBM in 2D to simulate a large number of cases of different environmental conditions

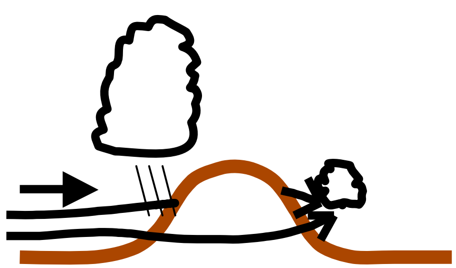
- Further develop the BMPD to capture the microphysical structures of the SBM simulations, and apply it in 3D for long term simulations that cover all types of environmental conditions

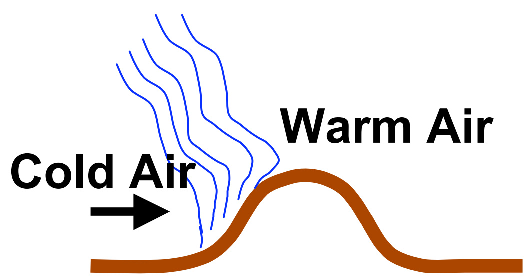
# Some Factors to Consider

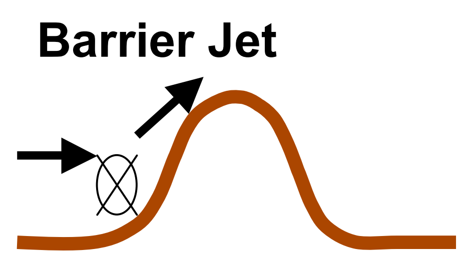
- Froude number $F = Nh/U$ is a simple parameter that can be used to distinguish flow over mountain or blocked

- Blocking induced instability (e.g., convergence on windward slope, lee side convergence of flow around barrier; differential advection of frontal air mass)

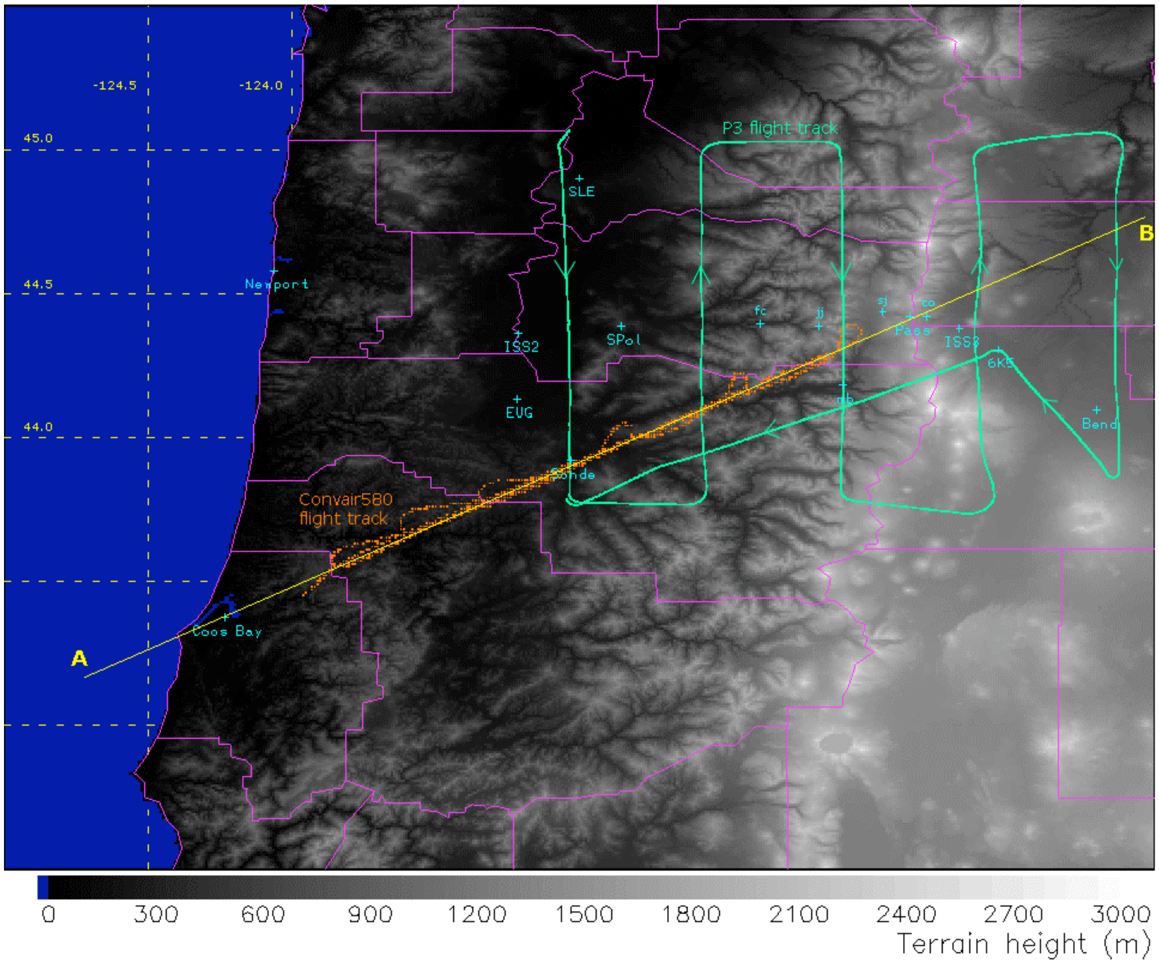
- Effects of moisture – saturation destabilizes the atmosphere; reduces mountain wave amplitude and drag; water loading and melting of snow can enhance blocking

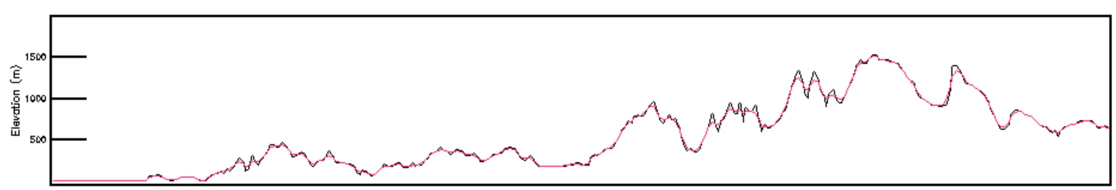


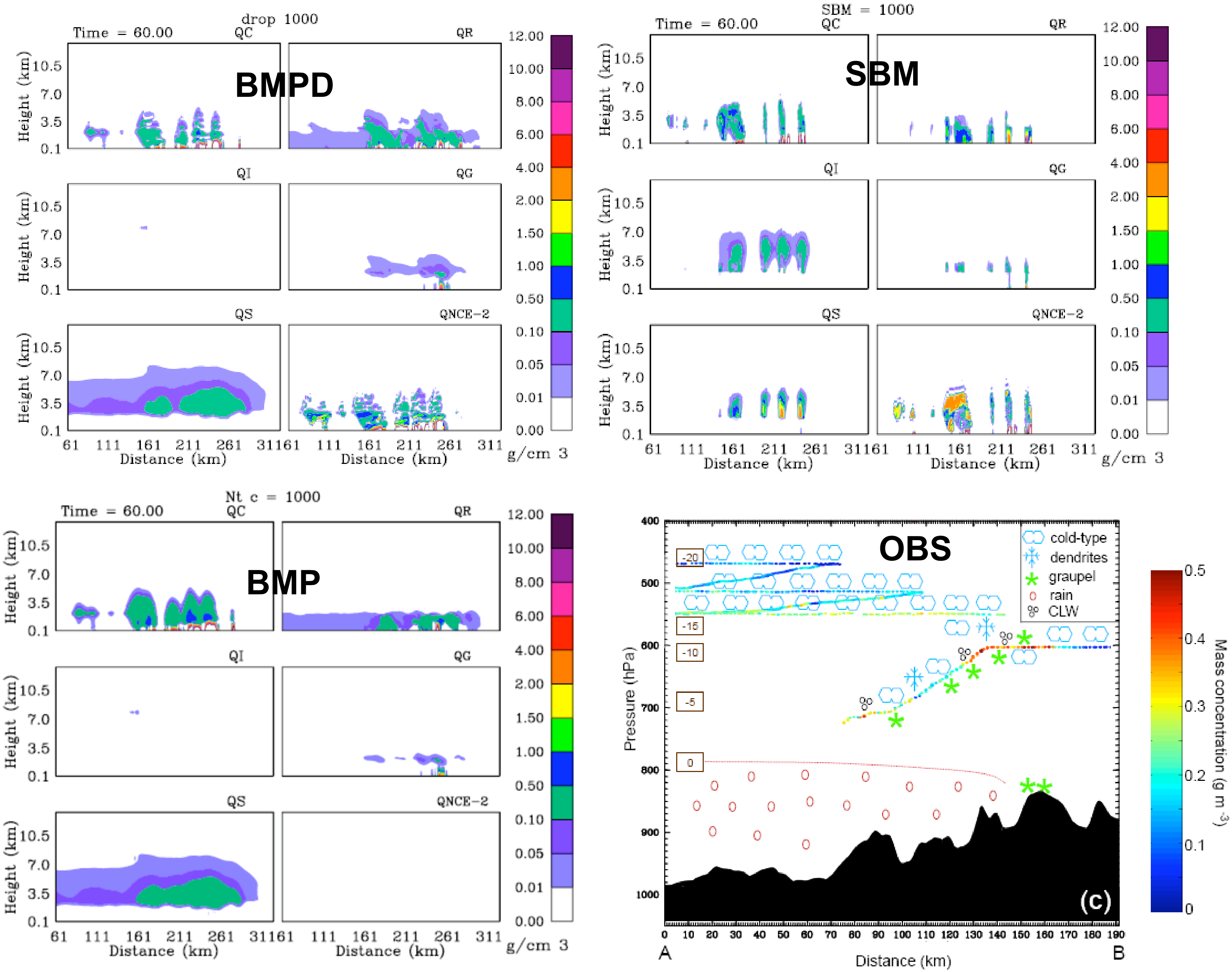


# The IMPROVE-2 Experiment: A WMO Case Study of 13-14 December 2001

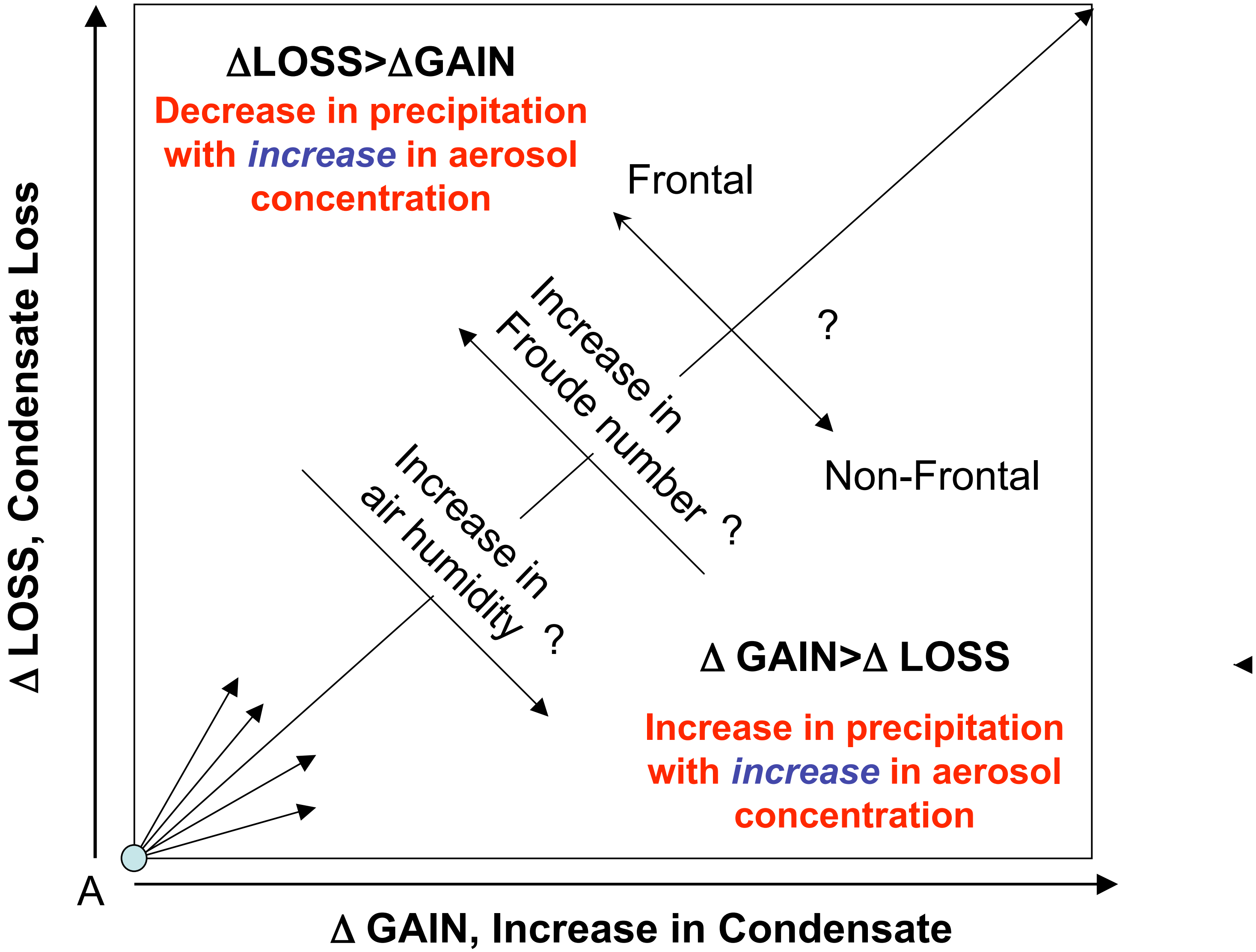




drop 1000
Time = 60.00
QC
QR
BMPD
QI
QG
QS
QNCE-2
Height (km)
Distance (km)
g/cm 3
SBM = 1000
SBM
Nt c = 1000
BMP
OBS
cold-type
dendrites
graupel
rain
CLW
Pressure (hPa)
Distance (km)
Mass concentration (g m -3)
A
B
(c)
-20
-15
-10
-5
0

# Possible scenarios of aerosol effects on precipitation for orographic clouds



# Future Work

- A large number of 2D SBM simulations of orographic clouds will be performed for different environmental conditions, including field studies with observational data for model evaluation (e.g., IMPROVE-2, SUPRECIP)
- Analysis of synoptic conditions to determine the frequency of occurrence of a few dominant types of conditions
- Combining the above modeling and analysis tasks, we hope to provide a more realistic assessment of aerosol effects on cold season orographic precipitation in the western U.S.
- Further development of the bulk cloud microphysics and prognostic droplet number scheme for climate modeling of combined greenhouse warming and aerosol effects

# Acknowledgement

- California Energy Commission PIERS
- NASA Energy and Water Cycle Studies (NEWS)